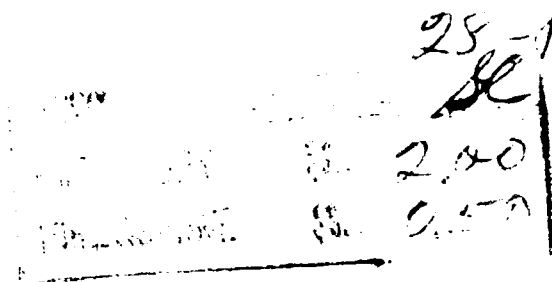


AD616981

FORWARDED BY:
CHIEF, BUREAU OF SHIPS TECHNICAL LIBRARY

Technical Report

Sixth Progress Report: Feasibility of
Developing an HY-180/210 Weldment



Applied Research Laboratory
United States Steel

Monroeville, Pennsylvania

March 1, 1965

Project No. 39.018-002(30)

NObs-88540 SS050-000 Task 1567 S-20000-6

THIS DOCUMENT MAY BE RELEASED WITH NO
RESTRICTIONS ON DISSEMINATION

| | | |
|-----------|----|--|
| COPY | OF | |
| HAB | | |
| MICROFILM | | |

SIXTH PROGRESS REPORT: FEASIBILITY OF DEVELOPING AN HY-180/210 WELDMENT
(39.018-002) (30) (a-ORD-NP-2) (S-20000-6)

March 1, 1965

By L. F. Porter, A. M. Rathbone, S. T. Rolfe, and K. E. Dorschu

Approved by J. H. Gross, Division Chief

Abstract

At the end of the fifth report period (October 31, 1964) on Bureau of Ships Contract No. NObs-88540, SS050-000, Task 1567, to investigate the feasibility of developing a submarine-hull weldment with a yield strength in the range 180 to 210 ksi (HY-180/210), several alloy systems offering considerable promise were still being evaluated.

Base-metal studies completed during the sixth report period have indicated that excellent combinations of strength and toughness (60 ft-lb at 0 F in 2-inch-thick plate at a yield strength of 180 ksi) were obtained in vacuum-induction-melted production heats of 12Ni-5Cr-3Mo steel. One carbon-martensite age-hardened Laboratory-melted steel absorbed about 70 ft-lb (at 0 f) at a yield strength of 183 ksi after conventional quenching and tempering and 120 ft-lb at 180 ksi after rapid heat treatment. Thus further studies on maraging steels, on carbon-martensitic age-hardened steels, and on rapid heat treatment are recommended as the primary approach to the development of an HY-180/210 base metal. Examination of these approaches at the production level will be undertaken to the extent permitted by the time remaining in the HY-180/210 feasibility study.

The development of filler metals that would be suitable for an HY-180/210 weldment continues to be a major problem. Some improvements in strength-toughness combinations have been observed, and special design and fabrication procedures offer promise of minimizing the strength requirements for an HY-180/210 weld metal.

The resistance of promising HY-180/210 weldments to stress corrosion is being intensively investigated by conventional tests and by K_{IC} stress-corrosion tests. A preliminary evaluation of the structural suitability of the most promising production materials is in progress.

Although the HY-180/210 feasibility study is not quite completed, the development of an HY-180/210 weldment appears feasible, and a program outlining the approaches recommended for an HY-180/210 development program is being prepared.

PROCESSING COPY

Introduction

During the period November 1, 1964 to February 28, 1965, work has continued on Bureau of Ships Contract No. NObs-88540, SS050-000, Task 1567, to investigate the feasibility of developing a submarine-hull weldment with a yield strength in the range 180 to 210 ksi (HY-180/210). The status of the HY-180/210 program as of October 31, 1964, including the work in progress at that time, was summarized in the fifth progress report.^{1)*} Most of the studies that were in progress at that time have been completed or significantly advanced during the sixth report period. The detailed results of these studies have been described in five individual reports, which are summarized in the present report. In addition, the present report describes the activities that are currently in progress or planned for the immediate future to investigate the feasibility of developing an HY-180/210 weldment.

BASE-METAL DEVELOPMENT

During the past report period, most of the Laboratory alloy-development feasibility studies have been completed and plans have been made for production heats of the most promising compositions. Plates from a 15-ton heat of 12Ni-5Cr-3Mo steel produced by vacuum-induction melting and vacuum pouring have exhibited exceptionally good notch toughness. Work has been initiated to determine the effect of composition on the response of steels to rapid heat treatment and plans have been made to further explore

*See References.

the practicality of strengthening heavy-gage (2 inches thick and over) production-size plates by rapid heat treatment.

Work to date has shown that there are three feasible approaches to the development of a steel with a yield strength of 180 to 210 ksi and a notch toughness in excess of 50 ft-lb Charpy V-notch energy at 0 F. They are (1) vacuum-melted maraging steels—both 12 and 18 percent nickel grades, (2) carbon-containing martensitic steels strengthened by age hardening, and (3) conventional quenched and tempered steels strengthened by rapid heat treatment.

Work Completed

Studies of Carbon-Containing Martensitic Steels for an HY-180/210 Weldment²⁾

Initial studies to develop an HY-180/210 steel suggested a number of approaches by which carbon-containing martensitic steels might be improved to meet the objective of a minimum yield strength of 180 ksi and a Charpy V-notch energy absorption of 50 ft-lb at 0 F. During the past year, a series of follow-up studies was undertaken on 3 to 9 percent nickel quenched and tempered steels. The studies involved an investigation of the effects of variation in carbon content, strengthening through the addition of cobalt, and secondary hardening through the addition of vanadium, tantalum, columbium, tungsten, titanium, and aluminum.

The studies showed that the steels must be tempered at low temperatures (about 400 F) to meet the yield-strength requirement unless

supplementary strengthening mechanisms are employed or the carbon content is increased above 0.25 percent. When the steels were strengthened by the addition of cobalt or secondary-hardening or age-hardening elements, the desired strength was obtained at a carbon content of 0.20 percent and at tempering temperatures as high as 1000 F. On a strength-toughness basis, the most attractive strengthening agents were cobalt, vanadium, tantalum, and aluminum. At a yield strength in the range 180 to 185 ksi, the most promising carbon-containing martensitic steels absorbed 39 to 44 ft-lb at 0 F, Figure 1. However, an 0.07C-9Ni-4Co-1Mo-0.3Al steel that obtains a portion of its strength from an age-hardening reaction exhibited exceptional notch toughness (140 ft-lb at 0 F) at a yield strength of 162 ksi.

A final series of Laboratory heats is being melted to confirm the properties observed for the most promising carbon-martensitic steels, and additional studies are being conducted on the 0.07C-9Ni-4Co-1Mo-0.3Al steel to determine whether the yield strength of the steel can be raised to a minimum of 180 ksi without excessive loss in toughness. From these final studies, a steel will be selected and produced on commercial facilities.

Work In Progress

Alloy Development

Quenched and Tempered Steels. Several additional Laboratory heats suggested by the studies described under Work Completed were melted, and 1/2-inch-thick plates have been evaluated. The steels contained 0.17C-7.5Ni-0.5Cr-1Mo-4Co and variations in vanadium and columbium. Yield strengths in

excess of 180 ksi were obtained for several of the steels; but at this yield strength, the Charpy V-notch energy at 0 F was in the range 40 to 46 ft-lb (somewhat below the desired minimum of 50 ft-lb). As a result, no production heat of a conventional quenched and tempered steel with a yield strength in excess of 180 ksi will be melted at this time.

Steels Strengthened by Carbon Martensite and Age Hardening. Results of a statistical program to develop a steel strengthened by a combination of carbon martensite and age hardening (described in the fourth³⁾ and fifth¹⁾ progress reports) were disappointing. The optimum composition predicted by the analysis was an 0.12C-11 to 13Ni-2½Cr-2½Mo-8Co steel. Heats of about this composition were made, and the mechanical properties of 1/2-inch-thick plates were determined. Although the steels did exhibit yield strengths in excess of 180 ksi, they did not show a strong age-hardening effect; and the maximum Charpy V-notch energy at 0 F was only 25 ft-lb.

As previously reported²⁾ a particularly promising steel is a low-carbon 9Ni-4Co-1Mo steel that contains 0.3 percent aluminum. This steel exhibits exceptional toughness at high yield strengths, presumably as a result of an age-hardening reaction involving aluminum. To investigate the characteristics of this steel in more detail, to determine the reproducibility of the mechanical properties, and to increase the strength of the steel to yield strengths in excess of 180 ksi, additional Laboratory studies have been initiated. A second 300-pound heat of the steel was produced to

evaluate the reproducibility of the steel. This heat also exhibited exceptional notch toughness (69 ft-lb Charpy V-notch energy at 0 F); and, apparently as a result of a slightly higher carbon content, exhibited a yield strength of 183 ksi. The chemical composition and the mechanical properties of the steel after aging for 5 hours at various temperatures are given in Table I, and the variation in strength and toughness with tempering temperature is shown in Figure 2. This steel is unique in that the notch toughness increases as the strength increases during aging at about 1000 F. A patent disclosure covering this steel is being prepared.

Carbon-Free Steels Strengthened by Age Hardening. The statistical study of carbon-free steels strengthened by age hardening (maraging steels) has been completed. The prediction equations obtained from this study have revealed no compositions that are superior to the 12 and 18 percent nickel grades extensively studied in the past.

Several Laboratory studies of both 12 and 18 percent nickel maraging steels have led to the conclusion that the optimum compositions for 180 ksi minimum yield strength maraging steels are as follows:

| <u>Ni</u> | <u>Cr</u> | <u>Mo</u> | <u>Co</u> | <u>Ti</u> | <u>Al</u> |
|-----------|-----------|-----------|-----------|-----------|-----------|
| 12.0 | 5.0 | 3.0 | — | 0.20 | 0.40 |
| 18.0 | — | 3.0 | 8.0 | 0.20 | 0.025 |

In both cases, carbon, silicon, manganese, phosphorus, and sulfur must be kept as low as possible.

The Laboratory studies have further revealed that of the two steels the 18 percent nickel steel exhibited superior notch toughness. As an additional check on these results, final Laboratory heats of the two steels were produced by vacuum-induction melting and the mechanical properties of 1/2-inch-thick plates were determined. The strength-toughness relations obtained for the two steels are shown in Figure 3. The notch toughness of the 12 percent nickel steel was lower than the 50 ft-lb objective at yield strengths over 180 ksi. The notch toughness of the 18 percent nickel steel was well in excess of the objective. The properties of the latter steel were so outstanding (over 60 ft-lb Charpy V-notch energy at 0 F at yield strengths of 185 to 190 ksi) that arrangements have been made to produce a 20-ton electric-furnace heat of the steel.

Melting Practice Studies

Production-size 1/2-, 1-, and 2-inch-thick plates of 12Ni-5Cr-3Mo steel have been produced from a 15-ton low-residual electric-furnace ingot remelted in a vacuum-induction furnace and alloyed and poured in vacuum (melted at Latrobe Steel Company by the Therm-I-Vac process). Chemical and metallographic analyses indicated that this special melting practice produced a maraging steel with very low levels of the residuals C, Mn, Si, P, S, and O and with a high degree of cleanliness. Mechanical-property evaluations of the plates showed that the steel had superior notch toughness (about 60 ft-lb Charpy V-notch energy at 0 F at yield strengths in excess of 180 ksi)

and that the toughness was not lowered significantly when the plate thickness was increased from 1/2 to 2 inches.

The chemical composition and mechanical properties of the steel are summarized in Table II. The strength-toughness relations for the 1/2-, 1-, and 2-inch-thick plates of the steel are compared in Figure 4 with the previously determined strength-toughness relations for various thicknesses of air-melted 12Ni-5Cr-3Mo maraging steels. The results indicate that the strength and notch-toughness objectives for an HY-180/210 steel can be achieved with the 12Ni-5Cr-3Mo steel by use of electric-furnace refining to produce a low-phosphorus, low-sulfur base steel that is then transferred to a production-size vacuum-induction furnace for carbon deoxidation, addition of oxidizable alloys, and vacuum pouring of the ingot. A detailed report of the processing and evaluation of the heat is being prepared. A second Therm-I-Vac heat is planned to confirm these results.

An electric-furnace heat has been scheduled to produce electrodes for evaluation of the Hopkins Process (consumable electrodes melted under slag) and of vacuum-consumable-electrode remelting. These are two other special melting practices that may improve the strength-toughness relation of the 12Ni-5Cr-3Mo steel.

Rapid Heat Treatment

Studies of the effect of steel composition on the response to rapid heat treatment have been initiated. Preliminary results indicate that all

quenched and tempered steels exhibit an improvement in mechanical properties when subjected to multiple-pass rapid-austenitizing treatments, though not to the same degree. Results on the 0.07C-9Ni-4Co-1Mo-0.3Al steel that exhibited a yield strength of 162 ksi when conventionally treated²⁾ were most encouraging. This steel showed relatively little change in strength at peak austenitizing temperatures in the range 1400 F to 1670 F (yield strength of 182 ksi at the lowest temperature, and 177 ksi at the highest temperature) compared with a decrease of 23 ksi for the 5Ni-Cr-Mo-V steel under similar conditions. The 9 percent nickel steel exhibited Charpy V-notch energy of about 120 ft-lb when rapidly heat-treated to a yield strength of about 180 ksi. The high notch toughness and lack of sensitivity to peak austenitizing temperatures make the 9 percent nickel steel particularly interesting for rapid heat treating.

Work Planned

After additional Laboratory studies have been conducted to determine the composition and melting limitations required to produce the 9Ni-4Co-1Mo-0.3Al steel, a production heat will be scheduled. A 20-ton heat of 18Ni-8Co-3Mo-0.20Ti-0.025Al steel is planned to determine whether the attractive properties achieved in the plates from Laboratory heats can be duplicated in plates from a production electric-furnace heat. A second Therm-I-Vac heat of 12Ni-5Cr-3Mo steel will be produced to confirm the favorable results obtained on the first heat. Plates of 12Ni-5Cr-3Mo steel

produced from Hopkins Process ingots and vacuum-consumable-electrode ingots will be evaluated. The feasibility of producing an HY-180/210 steel in heavy gages by rapid heat treatment will be further explored by conducting induction-heating trials on 2-inch-thick plates.

JOINING DEVELOPMENT

During the past report period, emphasis has been placed on (1) a study of the welding characteristics of rapidly heat-treated steel, (2) an evaluation of maraging steel filler metals, and (3) further evaluations of the Republic 0.25C-9Ni-4Co filler metal and several precipitation-hardened carbon-martensite filler metals. Two filler-metal development reports were issued.^{4,5)}

Work Completed

Weldability of Rapidly Heat-Treated 5Ni-Cr-Mo-V Steel

Previous work⁶⁾ has indicated that an unusually good combination of toughness (63 ft-lb at +80 F) and yield strength (200 ksi) can be achieved by rapid heat treatment of 5Ni-Cr-Mo-V steel and that this improvement is caused by the fine grain size that results from the rapid heat treatment. As discussed at the last progress meeting, preliminary results of a study to determine the effects of weld thermal cycles on the mechanical properties of rapidly heat-treated 5Ni-Cr-Mo-V steel indicated that the grain-coarsened region of the weld-heat-affected zone was slightly coarser than normal but that the grains in the bulk of the heat-affected zone were finer than usual.

Recently, results of tension tests of synthetically reproduced grain-coarsened heat-affected-zone microstructures indicated that this region was significantly weaker than the unwelded plate. To determine the effect of this weak region on the tensile properties of a composite heat-affected zone, two 1/2-inch-thick butt welds were fabricated by joining rapidly heat-treated 5Ni-Cr-Mo-V steel (1) by electron-beam welding and (2) by using 140 ksi yield strength covered electrodes. (The latter weldment was tested with the reinforcement intact so that the undermatching weld metal would not fracture prematurely.) The results of the mechanical-property tests of the two weldments, Table III, indicated that the narrowness of the fused and heat-affected zones in the electron-beam weldment apparently strengthened the joint by mechanical restraint so that the butt weld exhibited essentially the full strength of the unwelded plate. In addition, the results indicated that the grain-coarsened region of the weld-heat-affected zone in a conventional weldment of rapidly heat-treated 5Ni-Cr-Mo-V steel is not necessarily a weak link, as evidenced by the absence of fracture propagation in the heat-affected zones of the covered-electrode tension-test specimens.

Maraging Filler Metals

During the past report period, studies were completed on the effects of (1) gas shielding, (2) arc-travel speed, (3) welding-electrode composition, and (4) weld-metal heat treatment on the mechanical properties of 12Ni-Cr-Mo maraging-steel weld metals deposited by the AC inert-gas-

shielded metal-arc (MIG) process. The gas-shielding study showed that the use of outer auxiliary shielding increased the weld-metal yield strength about 4 to 7 ksi and increased the weld-metal toughness about 5 ft-lb at 80 F. The study of the effects of arc-travel speed indicated that an increase in travel speed (with a concomitant decrease in energy input and increase in the number of passes) caused a slight decrease in both weld metal strength and toughness. Several "high-purity" 12Ni-Cr-Mo maraging filler metals (containing residual elements at the level of 0.005 C, 0.01 Mn, 0.001 P, 0.003 S, and 0.01 Si) were deposited by using auxiliary shielding and relatively slow travel speeds. The best of these weld metals exhibited about 22 ft-lb at 80 F at a yield strength of 185 ksi. Several 12Ni-Cr-Mo weld metals were aged at different temperatures and times (in the range 850 to 1000 F for 3 to 6 hours). An aging treatment of 950 F for 6 hours appeared to produce the best combination of strength and toughness.

Work In Progress

Ni-Cr-Mo-Co Filler Metals

As described at the last progress meeting, a carbon-containing Ni-Cr-Mo-Co alloy system appears quite promising as an HY-180/210 filler metal in that the results of a statistical study indicated that 11 Ni-Cr-Mo-Co compositions should produce unusually good combinations of yield strength (180 to 190 ksi) and toughness (41 to 61 ft-lb). Consequently, 18 experimental Ni-Cr-Mo-Co filler metals were melted and rolled to rod. Problems

were encountered in softening the rods for subsequent wire drawing; however, a process-annealing technique was developed for softening the rods. The rods are currently being drawn to welding wire, and the wire will be deposited during the forthcoming report period and the weld metal evaluated.

Republic 0.25C-9Ni-4Co Filler Metal

AC MIG welding techniques have been developed for successfully depositing the 0.25C-9Ni-4Co filler metal in restrained joints, and an evaluation of the effects of welding parameters on weld-metal mechanical properties is currently being undertaken. As is the case for the previously described Ni-Cr-Mo-Co filler metals, an unusually good combination of strength and toughness has been achieved in 0.25C-9Ni-4Co weld metals deposited by the inert-gas-shielded tungsten-arc (TIG) process, and therefore the 0.25C-9Ni-4Co system is considered to offer excellent potential.

Work Planned

Until several of the studies currently in progress are completed, no new programs will be initiated.

STRUCTURAL EVALUATION

During the past report period, a test procedure for determining the susceptibility to stress-corrosion cracking of promising steels and weldments was developed. By using fracture-mechanics concepts, specimens are fatigue-cracked, exposed to a synthetic sea-water environment, and dead-weight-loaded

to failure in relatively short times. In addition, a preliminary study of the stress-corrosion behavior of U-bend specimens of 12 percent nickel maraging-steel weldments was completed.

Fatigue, fracture, and stress-corrosion tests have been started or will be started on the four steels listed under Base-Metal Development considered extremely promising as an HY-180/210 weldment.

Work Completed

Development of a K_{IC} Stress-Corrosion Test Specimen⁷⁾

Preliminary reports by the Naval Research Laboratory indicate that the effective fracture toughness of certain materials may be reduced if a flaw in the material can extend by stress corrosion to a critical size. Therefore, the Applied Research Laboratory initiated a study to develop a K_{IC} stress-corrosion test that would be suitable for investigating the reported phenomenon.

The results of the study indicate that by appropriate modification, the standard K_{IC} slow-bend fracture-toughness test can be used to demonstrate the effect of stress corrosion on fracture toughness. The modification consists of notching the specimen face so that plane-strain fracture can be obtained in relatively small specimens of tough materials. The fatigue-crack area is surrounded by the appropriate corrosive environment and the specimen is dead-weight-loaded as a cantilever beam, as shown in Figure 5. Typical

photomicrographs showing the fatigue, stress-corrosion, and plane-strain portions of the fracture surfaces are shown in Figure 6.

Preliminary results on a 12Ni-5Cr-3Mo maraging steel (yield strength of about 175 ksi and Charpy V-notch energy absorption of about 35 ft-lb) have shown that this steel failed by plane-strain fracture at values ranging from 0.8 K_{IC} at 10 hours to 0.3 K_{IC} at 400 hours when the fatigue crack was exposed under stress to synthetic sea water, Figure 7. To date similar failures have not been observed in the 5Ni-Cr-Mo-V experimental HY-130/150 steel.

These results confirm the report that the effective fracture toughness of certain materials can be significantly reduced by the stress-corrosion extension of a sharp (fatigue) crack to the critical flaw size. Other materials of interest for submarine-hull fabrication are now being evaluated by this K_{IC} stress-corrosion-test technique.

Stress-Corrosion Behavior of 12 Percent Nickel Maraging-Steel Weldments⁸⁾

As part of the Applied Research Laboratory's program to determine the feasibility of developing an HY-180/210 weldment, studies were conducted to determine the stress-corrosion properties of 12Ni-5Cr-3Mo maraging-steel weldments in marine environments. Stress-corrosion tests were conducted with welded U-bend specimens in quiescent and flowing sea water, in the tidal zone and in a marine atmosphere.

Stress-corrosion cracking was observed in 6 to 17 days in specimens exposed in the three sea-water environments; no significant difference in cracking time was observed among the environments. In the marine atmosphere, the specimens showed an appreciably higher resistance to stress-corrosion cracking; the shortest cracking time in this environment was 62 days. Metallographic examination showed that, generally, the cracks initiated in the weld metal and propagated in the weld metal and in the heat-affected zone. The absence of base-metal cracking (away from welds) in some specimens exposed for 170 days is regarded as evidence that the base metal may be resistant to cracking in marine environments. It also appears that carbon steel can prevent cracking by cathodically protecting 12Ni-5Cr-3Mo weldments.

Further tests will be conducted on 12 percent nickel maraging steel (1) to confirm the present results indicating that this steel is resistant to stress-corrosion cracking in the unwelded condition in marine environments and (2) to establish the conditions under which cathodic protection by carbon steel can be expected to prevent cracking.

Work In Progress and Planned

As described under Base-Metal Development, four steels appear extremely promising as an HY-180/210 weldment. These four steels are Laboratory vacuum-induction-melted heats of 18Ni-8Co-3Mo and 9Ni-4Co-1Mo-0.3Al steels, a 12Ni-5Cr-3Mo 15-ton vacuum-induction-melted steel, and the 5Ni-Cr-Mo-V steel rapidly heat treated.

The following preliminary information on the structural suitability of these steels is being obtained:

1. Mechanical properties including stress-strain curves, modulus of elasticity, secant modulus, and tangent modulus.
2. Plain-plate fatigue tests in air and synthetic sea water.
3. K_{IC} stress-corrosion tests.
4. Drop-weight tear tests.
5. Plane-strain fracture-toughness tests to obtain K_{IC} values.

In addition, U-bend stress-corrosion tests at Kure Beach and Laboratory tension tests in synthetic sea water are being conducted on 18Ni-8Co-2.6Mo and 12Ni-5Cr-3Mo maraging steels. Various conditions (solution-annealed, aged, welded and aged, weld bead as-deposited, etc) of plain plates and bead-on-plate welded specimens are being tested to determine the effects of these conditions on stress-corrosion cracking.

References

1. L. F. Porter, A. M. Rathbone, S. T. Rolfe, and K. E. Dorsch, "Fifth Progress Report: Feasibility of Developing an HY-180/210 Weldment," Applied Research Laboratory Report 40.018-002(27), (S20000-5), December 1, 1964.
2. D. S. Dabkowski, S. J. Manganello, and L. F. Porter, "Studies of Carbon-Containing Martensitic Steels for an HY-180/210 Weldment," Applied Research Laboratory Report 39.018-002(28), (S21102 and S-21103-2), March 1, 1965.
3. L. F. Porter, A. M. Rathbone, S. T. Rolfe, and K. E. Dorsch, "Fourth Quarterly Progress Report: Feasibility of Developing an HY-180/210 Weldment," Applied Research Laboratory Report 40.018-002(22), (S-20000-4), July 1, 1964.
4. W. A. Fragetta, "Maraging Steel Filler Metals, The Effect of Wire Processing," Air Reduction Report No. RE-65-021, (CRE-34), March, 1965.
5. W. A. Fragetta, "Evaluation of a 9Ni-4Co-.25C Filler Metal," Air Reduction Report No. RE-65-028, (CRE-34), March, 1965.
6. R. P. Haak, K. H. Kramer, L. F. Porter, and R. W. Zabelsky, "Rapid Heat Treatment of 5Ni-Cr-Mo-V Steel," Applied Research Laboratory Report 40.018-002(24), (S-21302-1), December 1, 1964.
7. S. T. Rolfe, "Development of a K_{IC} Stress-Corrosion Test Specimen," Applied Research Laboratory Report 39.018-002(29), (S-23304), March 1, 1965.
8. A. W. Loginow, "Stress-Corrosion Behavior of 12 Percent Nickel Maraging-Steel Weldment," Applied Research Laboratory Report 40.001-100(3), (S-23309), December 31, 1964.

Table I

Chemical Composition and Effect of Aging Temperature on the Mechanical Properties of 9Mn-4Co-1Mo-0.3Al Steel (Heat No. 76105)

| Check Analysis—Percent | | | | | | | | | | |
|---------------------------------|-----------------------------------|-----------------------|-------------------------|----------------------|-----------------------------------------|-------|--------------|------|-----------------|-----------------|
| | Mn | P | S | Si | Ni | Cr | Co | Mo | Al ⁺ | N ⁺⁺ |
| 0.083 | 0.10 | 0.002 | 0.006 | 0.087 | 8.73 | <0.10 | 4.06 | 1.03 | 0.23 | <0.001 |
| +Acid soluble. | | | | | | | | | | |
| ++Kjeldahl determination. | | | | | | | | | | |
| The Effect of Aging Temperature | | | | | | | | | | |
| Aging Temperature, F | Yield Strength (0.2% Offset), ksi | Tensile Strength, ksi | Elongation in 1 inch, % | Reduction of Area, % | Charpy V-Notch Energy Absorption, ft-lb | | Hardness, Rc | | | |
| | | | | | +80 F | 0 F | | | | |
| As-quenched | 152 | 194 | 16.0 | 66.5 | 58 | 57 | | | | 43.0 |
| 400 | 164 | 194 | 16.0 | 67.8 | 59 | 56 | | | | 43.0 |
| 600 | 168 | 189 | 15.5 | 67.6 | 54 | 52 | | | | 42.0 |
| 800 | 170 | 183 | 16.0 | 65.8 | 53 | 50 | | | | 41.0 |
| 900 | 173 | 184 | 18.0 | 69.3 | 62 | 59 | | | | 41.0 |
| 950 | 178 | 186 | 18.0 | 68.8 | 69 | 69 | | | | 42.5 |
| 1000 | 183 | 190 | 17.0 | 72.0 | 64 | 69 | | | | 42.0 |
| 1050 | 178 | 181 | 17.5 | 70.7 | 80 | 69 | | | | 41.0 |

NOTE: All plate samples austenitized at 1500 F for 1 hour, water-quenched, aged at the indicated temperatures for 5 hours, and water-quenched. All results are the average of duplicate longitudinal 0.252-inch-diameter tension-test specimens and standard Charpy V-notch impact-test specimens from the mid-thickness location.

(39.018-002) (30)

UNITED STATES STEEL

Table II

Chemical Composition and Mechanical Properties of 1/2-, 1-, and 2-Inch-Thick Plates Produced From a 15-Ton Vacuum-Induction-Melted Heat of 12Ni-5Cr-3Mo Steel (Laboratory Heat No. 50169)

Check Analysis—Percent

| C | Mn | P | S | Si | Ni | Cr | Mo | Ti | Al ⁺ | N ⁺⁺ | O |
|-------|-------|-------|-------|-------|-------|------|------|------|-----------------|-----------------|--------|
| 0.002 | 0.018 | 0.004 | 0.005 | 0.048 | 12.20 | 5.07 | 3.12 | 0.21 | 0.25 | 0.008 | 0.0004 |

⁺Acid soluble.

⁺⁺Kjeldahl determination.

Mechanical Properties

| Plate Thickness, inches | Plate No. | Specimen Orientation | Yield Strength (0.2% Offset), ksi | Tensile Strength, ksi | Elongation in 1 inch, % | Reduction of Area, % | Charpy V-Notch Energy Absorption, ft.-lb. -80 F | 0 F |
|-------------------------|-----------|----------------------|-----------------------------------|-----------------------|-------------------------|----------------------|----------------------------------------------------|-----|
| 1/2 | 338790 | Longitudinal | 182 | 173 | 16.0 | 65.5 | 71 | 65 |
| | | Transverse | 185 | 195 | 16.0 | 65.5 | 53 | 64 |
| 1 | 338789 | Longitudinal | 179 | 189 | 16.0 | 65.3 | 63 | 61 |
| | | Transverse | 181 | 190 | 15.0 | 64.1 | 54 | 49 |
| 2 | 338788 | Longitudinal | 189 | 195 | 16.0 | 66.2 | 57 | 52 |
| | | Transverse | 188 | 194 | 16.0 | 65.3 | 56 | 47 |

NOTE: Plate samples production-solution-annealed at 1500 F for at least 1 hour per inch of thickness, laboratory-aged at 900 F for 30 hours and water-quenched. The results are the average of duplicate 0.252-inch-diameter tension-test specimens and standard Charpy V-notch impact-test specimens.

(39.018-002) (30)

UNITED STATES STEEL

Table III

**Results of Preliminary Studies of the Welding Characteristics
of Rapidly Heat-Treated 5Ni-Cr-Mo-V Steel**

A. Mechanical Properties of 1/2-Inch-Thick Electron-Beam Weldments*

| <u>Specimen</u> | <u>Yield Strength (0.2% Offset), ksi</u> | <u>Tensile Strength, ksi</u> | <u>Reduction of Area, %</u> | <u>Fracture Location</u> | <u>Charpy V-Notch Energy Absorption at 0 F., ft-lb</u> |
|----------------------------------|--------------------------------------------------|--------------------------------------|-------------------------------------|------------------------------|----------------------------------------------------------------|
| Unwelded plate | 196 | 207 | 61 | — | 65 |
| Transverse butt- welded plate | 191 | 203 | 49 | Fused Zone | — |
| HAZ | — | — | — | — | 42 |
| Fused zone | — | — | — | — | 54 |

B. Transverse Tensile Properties of 1/2-Inch-Thick Butte Welds
Fabricated With 140 Ksi Yield-Strength Filler Metal**

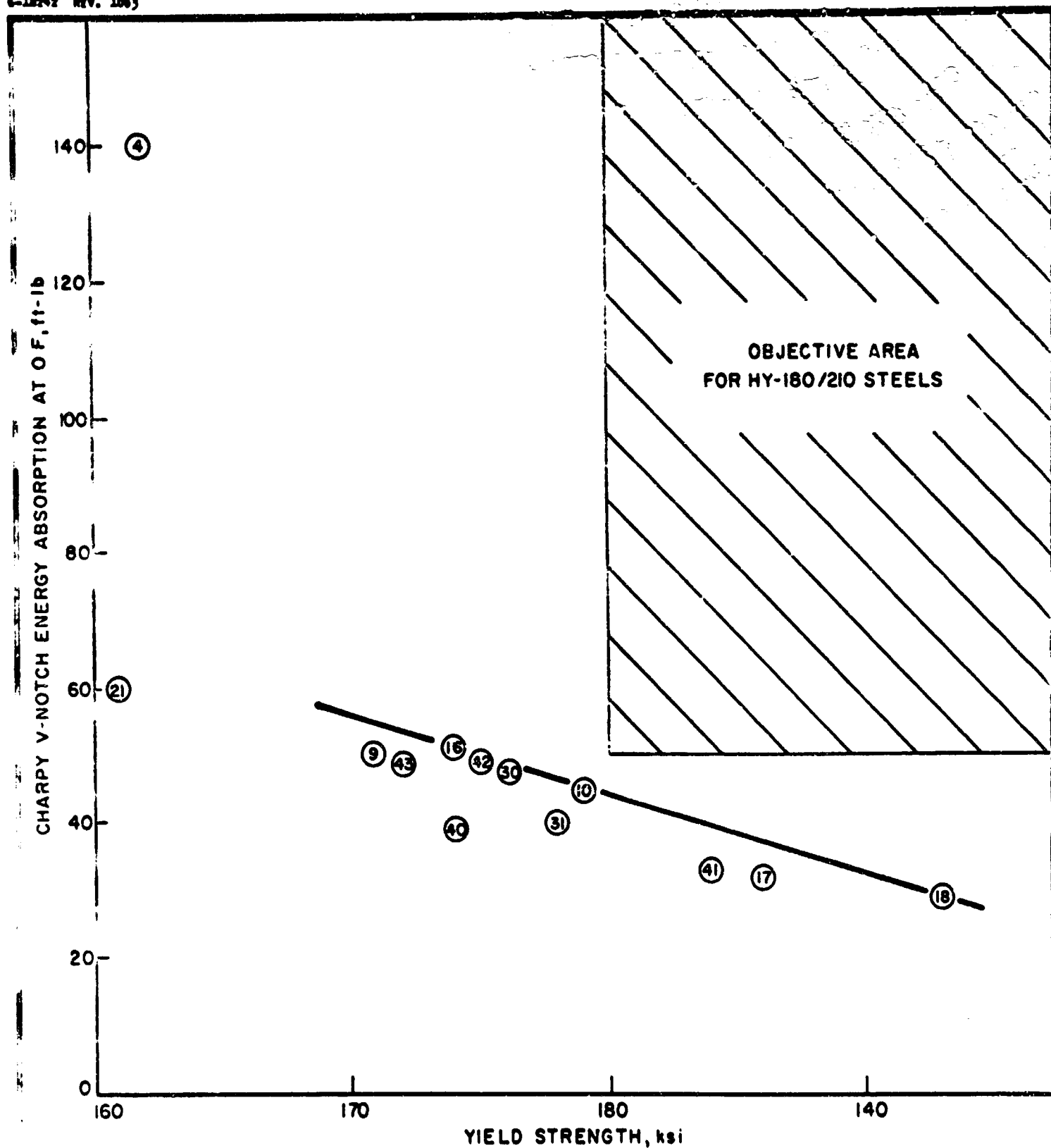
| <u>Specimen Number</u> | <u>Tensile Strength, ksi</u> | <u>Fracture Location</u> |
|----------------------------|--------------------------------------|------------------------------|
| 1 | 177 | Base metal |
| 2 | 179 | Base metal |
| 3 | 177 | Weld metal |
| 4 | 178 | Weld metal |
| 5 | 179 | Weld metal |
| 6 | 178 | Weld metal |

*The electron-beam weldment contained an 0.06-inch-wide fused zone and an 0.06-inch-wide heat-affected zone. The grain-coarsened region was about 0.01-inch wide.

**The butt welds were tested with the reinforcement intact.

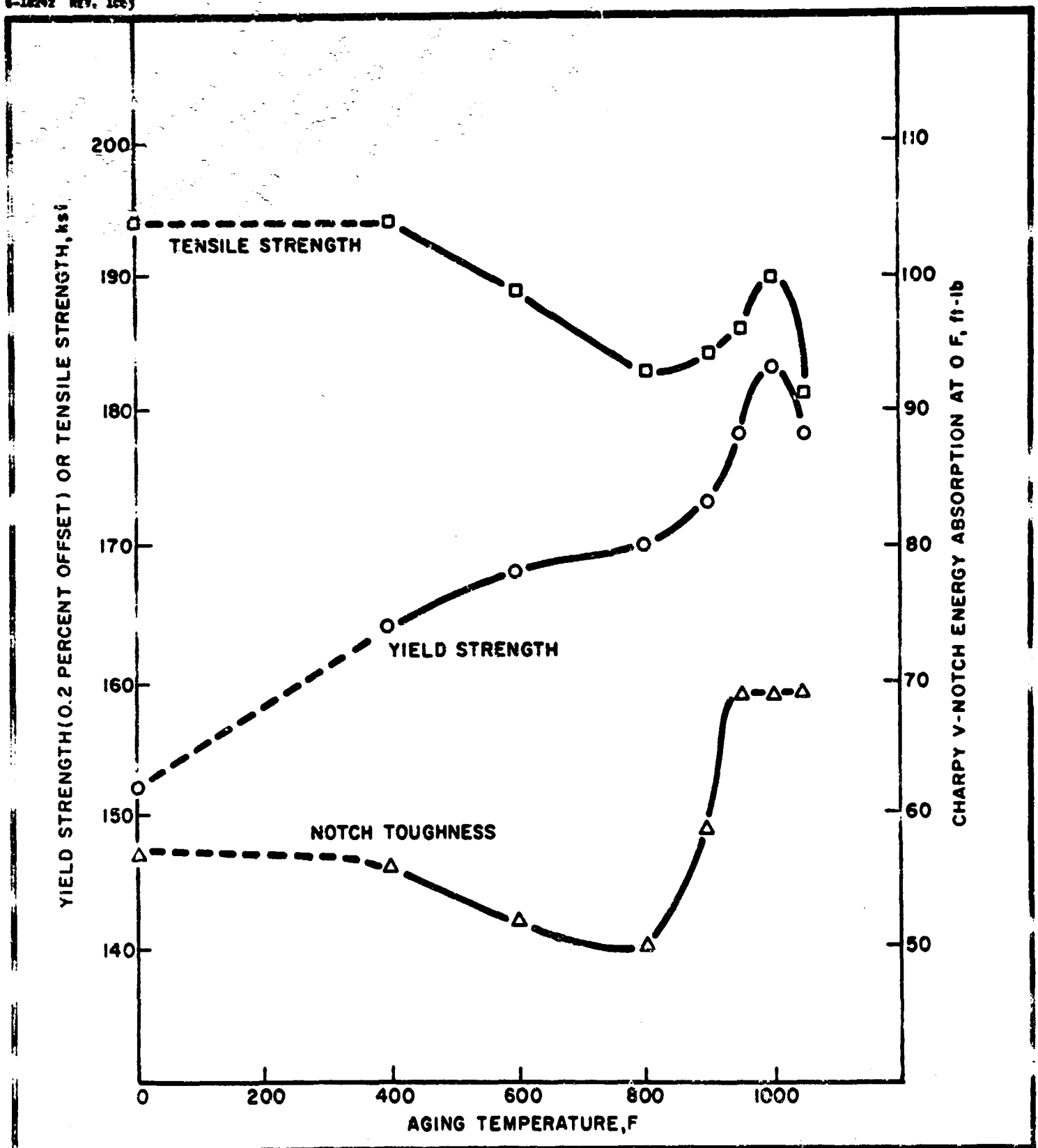
(39.018-002) (30)

UNITED STATES STEEL



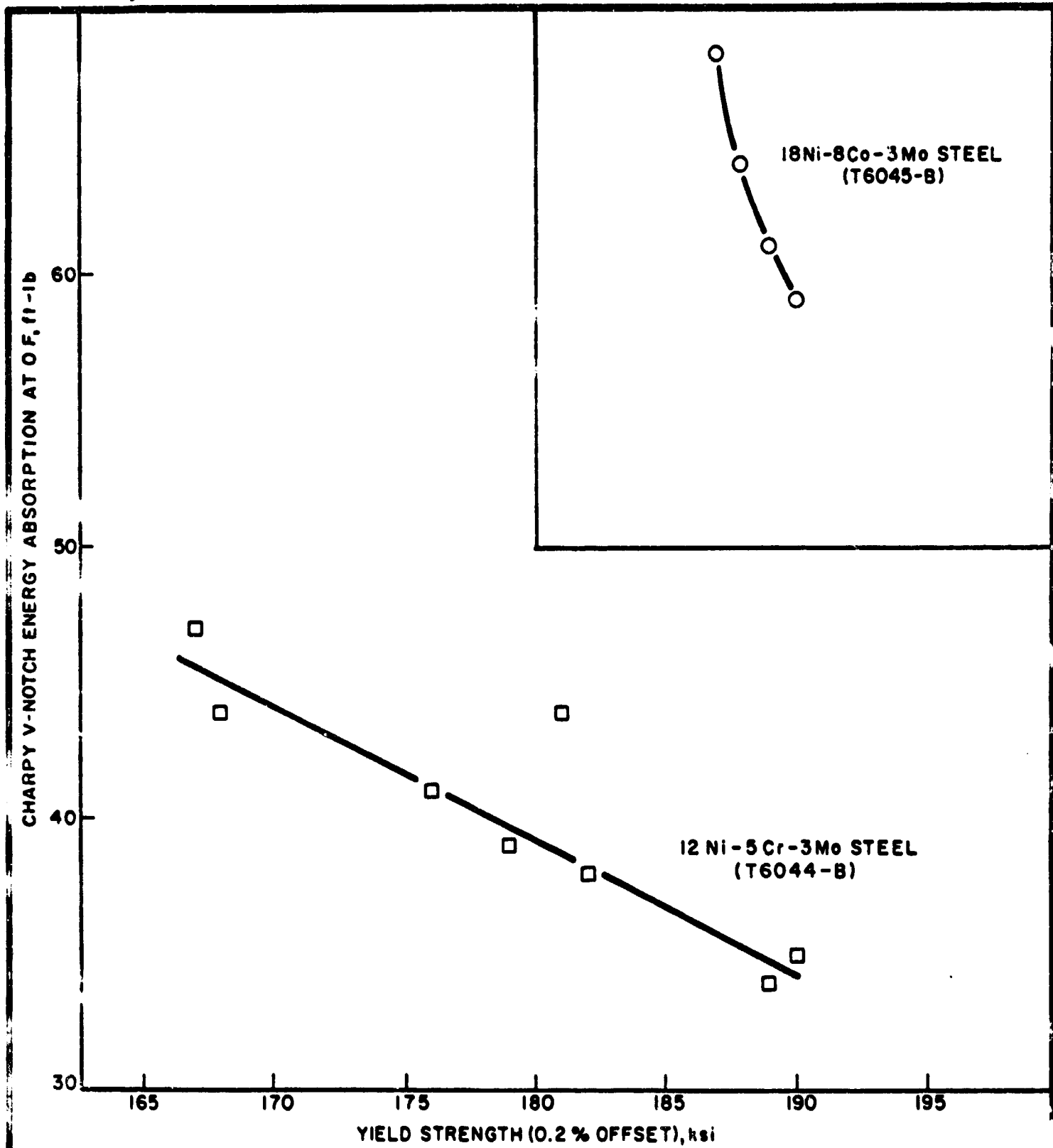
YIELD-STRENGTH-NOTCH-TOUGHNESS RELATION FOR MOST PROMISING STEELS

| | | | | |
|--------------------|--------------------|------------------------------------|------------------------------------------------------------------------|--------------------|
| DRAWN BY G.A.Z. | CHK'D BY D.S.D. | APPROVED BY J.H.G. | UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA. | FIGURE NO. 1 |
| DRAWING No. | | PROJECT No. | | |
| ARL 18-524 | | 39,018-002 (30) DATE 2-15-65 | | |



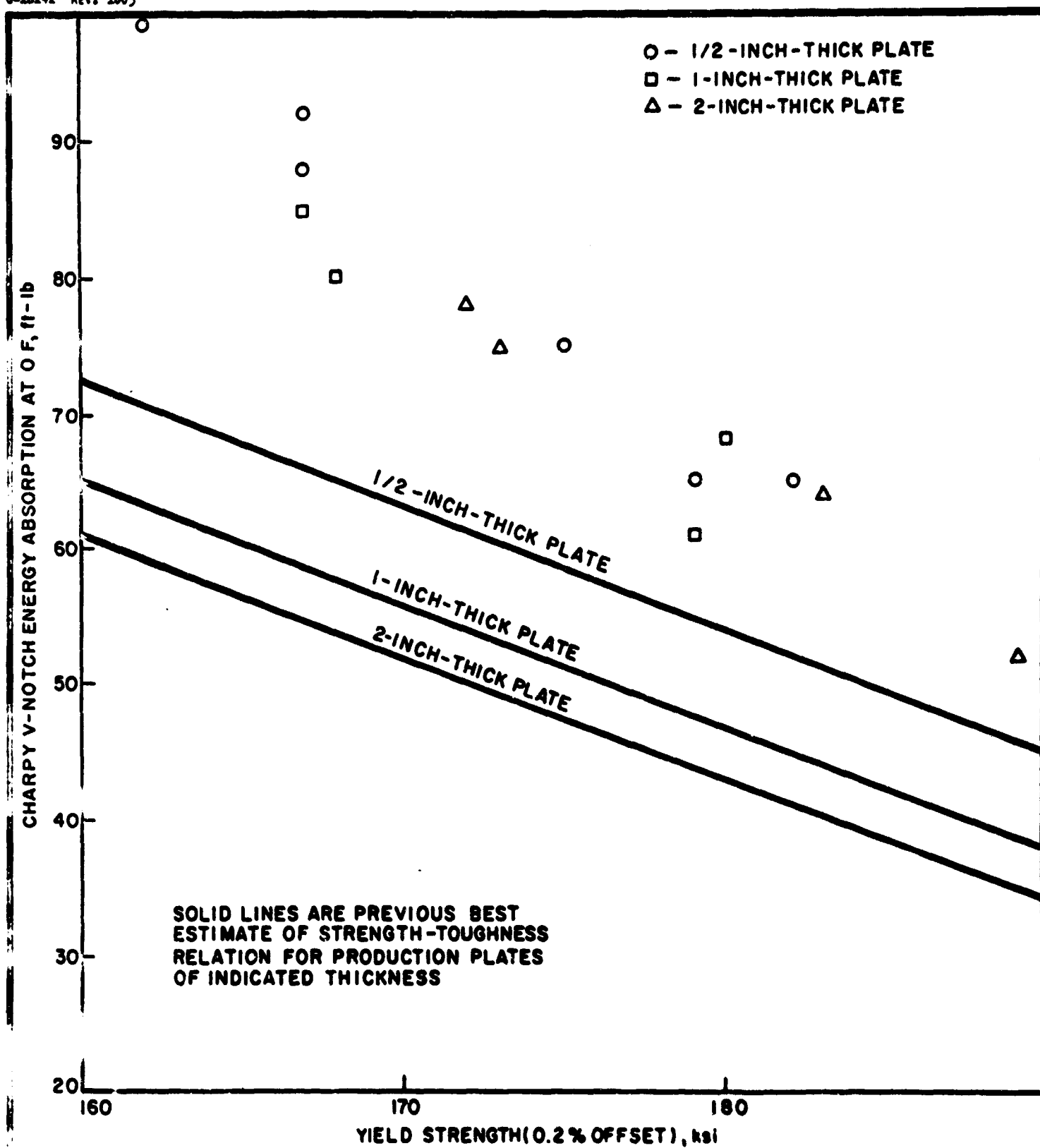
EFFECT OF AGING TEMPERATURE ON THE MECHANICAL PROPERTIES OF
LABORATORY TREATED 9Ni-4Co-1Mo-0.3Al STEEL (HEAT NO. T6105)

| | | | | |
|---------------------------|--------------------|--------------------------------|------------------------------------------------------------------------|--------------------|
| DRAWN BY G.A.Z. | CHK'D BY D.S.D. | APPROVED BY J.H.G. | UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA. | FIGURE NO. 2 |
| DRAWING No. ARL 18-555 | | PROJECT No. 39,018-002 (30) | | |
| | | DATE 3-16-65 | | |



YIELD-STRENGTH-NOTCH-TOUGHNESS RELATION FOR TWO CARBON-FREE AGE-HARDENING EXPERIMENTAL STEELS

| | | | | |
|----------------------|----------------------|-----------------------------------|------------------------------------------------------------------------|--------------------|
| DRAWN BY G. A. Z. | CHK'D BY D. S. D. | APPROVED BY J. H. G. | UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA. | FIGURE NO. 3 |
| DRAWING No. | | PROJECT No. | | |
| ARL 18-556 | | 39,018-002(30) DATE 3-16-65 | | |



YIELD-STRENGTH-NOTCH-TOUGHNESS RELATION FOR 1/2-, 1-, AND 2-INCH-THICK PLATES OF VACUUM-INDUCTION-MELTED 12Ni-5Cr-3Mo STEEL (HEAT NO. 50169)

| | | | | |
|---------------------------|----------------------|--------------------------------|------------------------------------------------------------------------|--------------------|
| DRAWN BY G. A. Z. | CHK'D BY D. S. D. | APPROVED BY J. H. G. | UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA. | FIGURE NO. 4 |
| DRAWING No. ARL IS-557 | | PROJECT No. 39.018-002 (30) | | |
| | | DATE 3-16-65 | | |

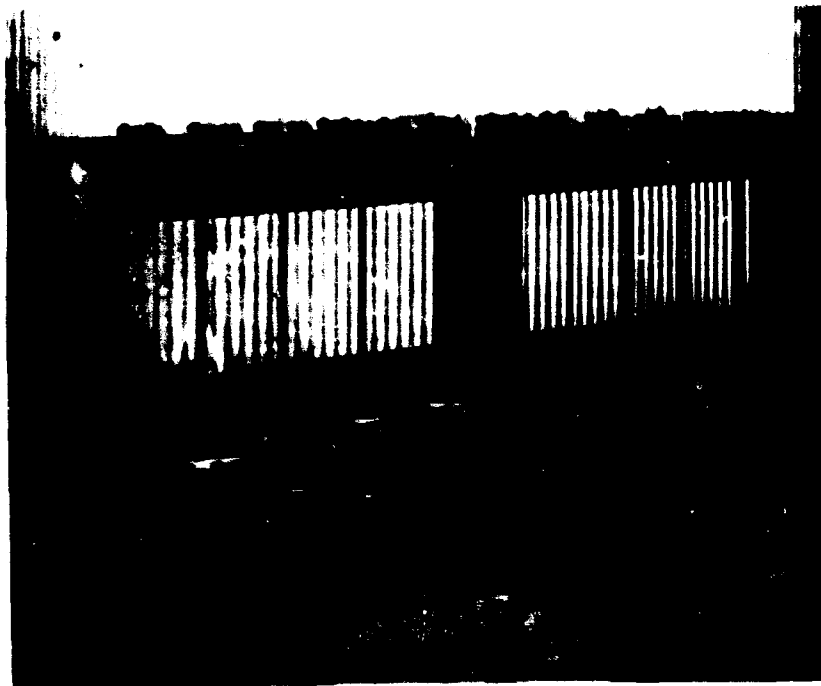
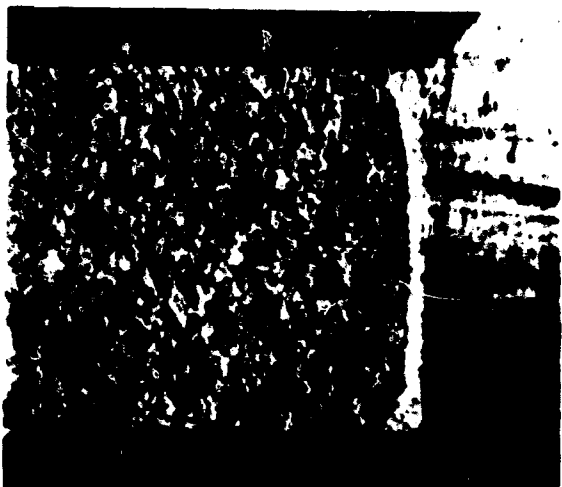
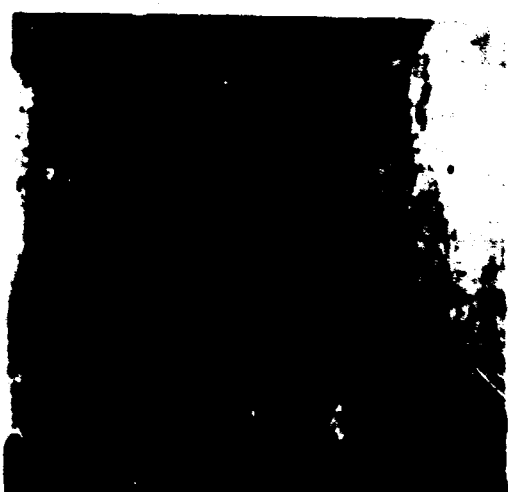


Figure 5. K_{IC} stress-corrosion test stand.



Air. (X4)



Synthetic sea water. (X4)

Fatigue crack —
 Stress-corrosion crack —
 Plane-strain crack —

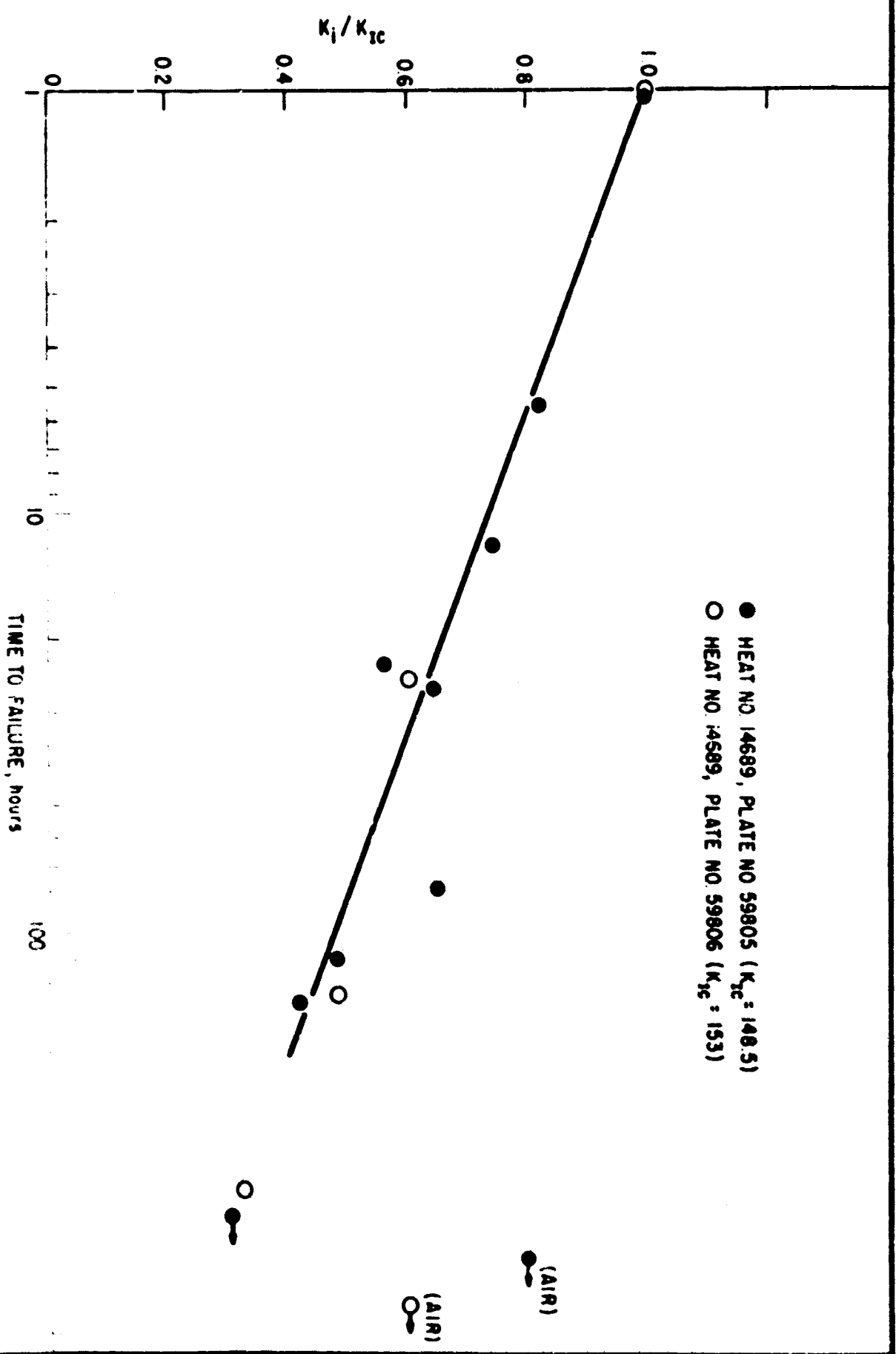
Figure 6. Typical 12Ni-5Cr-3Mo K_{1c} stress-corrosion specimens tested in air and synthetic sea water.

P-5025A-1
P-5025A-2

(39.018-002) (30)

UNITED STATES STEEL

Figure 6



K_i / K_{ic} STRESS-CORROSION RESULTS FOR 12 Ni-5 Cr-3 Mo STEEL
 TESTED IN SYNTHETIC SEA WATER

| | | | |
|-----------------------------------------------------------------------|-------------------|----------------------|-----------------|
| DRAWN BY M M | CHECKED BY STR | APPROVED BY J M G | DATE 10-1-65 |
| ARL 18-560 | | | |
| UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA | | | |